

SUBARCSEC EMISSION IN SEYFERT GALAXIES: THE NUCLEAR COMPONENT IN THE *L*- AND *M*-BANDS

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ABSTRACT

We present deep *L*- ($3.8\ \mu\text{m}$) and *M*- ($4.7\ \mu\text{m}$) band imaging with *ISAAC* on the *ESO VLT* with unprecedented spatial resolution of the nearby Seyfert 2 galaxies NGC 7496 and NGC 7582 and the Seyfert 1 galaxy NGC 7213, all at comparable distance. The unresolved nuclear component dominates the emission within the central 90 pc region, while the host galaxy accounts for up to 50 % of the integrated emission at both wavelengths within the detected sizes of ~ 1 kpc in the *L*-band and ~ 0.5 kpc in the *M*-band. The overall morphology of the extended component follows the general isophote pattern defined by the near-infrared continuum of the galaxies. However, the central 300 pc regions show much more ordered elliptical isophotes than in the near-infrared. In particular, emission in the *L*- and *M*-bands shows well defined central point sources in the two Seyfert 2s. The brightness of the Seyfert nuclei in the *LM*-bands indicates that the Seyfert 2 NGC 7582 harbors as powerful nucleus as that in the Seyfert 1 NGC 7213, while the Seyfert 2 NGC 7496 is intrinsically weaker. In NGC 7582, we have detected the circumnuclear star forming ring in the *L*-band.

Subject headings: galaxies:active – galaxies:nuclei – galaxies:Seyfert – galaxies:spiral – infrared:galaxies

1. INTRODUCTION

The unified model for Seyfert galaxies postulates that Seyfert type 1 (S1) and type 2 (S2) nuclei are intrinsically similar, the observed differences between them being due to obscuration and viewing angle to the AGN. The nuclear continuum and the broad line region (BLR) of S1s are obscured from direct view in S2s by an optically and geometrically thick torus of gas and dust. This torus absorbs a significant fraction of the nuclear high energy emission, and reradiates it into the infrared (IR; e.g. Antonucci 1993).

A promising method to test the validity of the unified model is to perform high spatial resolution imaging in the *LM*-bands, $3 - 5\ \mu\text{m}$. Recent near-IR (NIR; *JHK*-bands, $1 - 2.5\ \mu\text{m}$) continuum imaging studies of Seyfert nuclei (e.g. Kotilainen & Ward 1994; Alonso-Herrero, Ward & Kotilainen 1996) have shown that the stellar contribution decreases with increasing wavelength, dominating in the *JH*-bands but accounting only for ~ 50 % of the emission in the *K*-band, particularly in S2s. If this trend persists towards longer wavelengths, the $3 - 5\ \mu\text{m}$ range should give us a much cleaner view of the nuclear region in Seyferts. Furthermore, with reduced extinction effects, that spectral region may start to reveal the presence, and even the structure, of the putative obscuring dusty torus or disk surrounding the Seyfert nuclei. The internal regions of the torus may reach high temperatures ($T \geq 1000$ K) and thus radiate at NIR wavelengths in S1s whereas this emission may remain optically thick in S2s. However, dust emitting in the $3 - 5\ \mu\text{m}$ range should arise from regions further away from the nucleus, being thus cooler ($T = 600$

– 800 K) and equally traceable in both Seyfert types. By modeling the *LM*-band luminosity profiles, it should be possible to assess the contributions from stellar and dust emission, which should be similar in both Seyfert types if the unified model is valid.

Previous studies in the $3 - 5\ \mu\text{m}$ range are scarce. Pioneering work by Kotilainen et al. (1992), Zhou, Wynn-Williams & Sanders (1993) and Alonso-Herrero et al. (1996; 2001) lack sufficient spatial resolution, sensitivity and field-of-view to detect the host galaxies and therefore do not allow for an accurate separation of the central nuclear component. Also, the available imaging only allows photometry with large apertures ($\geq 3''$). Recently, diffraction-limited imaging in the *LM*-bands using adaptive optics (AO) of the nearby prototype S2 galaxy NGC 1068 revealed a wealth of information (Marco & Alloin 2000). These observations reveal in NGC 1068 a core with radius < 8 pc, a disk structure of ~ 80 pc size and extended emission perpendicular to the disk of ~ 100 pc size.

This paper presents our first results from an *ISAAC* program on the *ESO VLT* devoted to subarcsec resolution images in the *LM*-bands of nearby S1 and S2 galaxies. The results focuses on the two S2s, NGC 7496 at $z = 0.00550$ and NGC 7582 at $z = 0.00525$, and one S1, NGC 7213 at $z = 0.00597$. The excellent image quality provided by *VLT* lead to unprecedentedly high spatial resolution images in the *LM*-bands, $0''.4$ and $0''.6$ FWHM, respectively, corresponding to physical distances between 70 and 90 pc.

2. OBSERVATIONS

Broad-band images of the Seyferts in the *L*- ($3.8\ \mu\text{m}$) and *M*- ($4.7\ \mu\text{m}$) bands were obtained with *ISAAC* on the

ESO VLT UT Antu in service mode during 2000 September - October. The observations were taken in chopping mode. Each final image is the result of stacking 46 (*L*) or 104 (*M*) individual chopped frames. In addition to chopping, consecutive frames were taken after nodding the telescope to typically $20''$ distance on the sky. The total integration time for all galaxies was 25 minutes in the *L*-band and 45 minutes in the *M*-band. The field-of-view of the images is $73''$, thus, these are the first large-format array *LM*-band images of any Seyfert galaxies. Previously published images in these bands cover smaller field-of-views by a factor of ≥ 3 . The instrumental PSF shape was determined from images of standard stars taken close in time to the galaxy images. Occasional image elongations were seen in the core of the PSF caused by field instabilities produced by the secondary mirror during chopping. These image elongations are generally < 0.5 FWHM in both bands. Additional *JHK*-band images were taken with *SOFI* on the *ESO NTT*. These images have a typical seeing of $1''$ FWHM and integration times of 75 seconds in *JH*- and 100 seconds in *K*-band.

3. RESULTS

Fig. 1 shows the *LM*-band images of the three galaxies. All exhibit extended emission, traceable up to $\sim 3 - 7''$ from the nucleus. In the *L*-band, the extent of this emission ranges from 500 pc in NGC 7496 to 1.2 kpc in NGC 7213, whereas in the *M*-band, it is more compact and extends from 150 pc in NGC 7496 to 500 pc in NGC 7582.

The S1 galaxy NGC 7213 is a face-on SA0, with identical morphology from the optical to the *M*-band. At 8.4-GHz, it is unresolved, the core region being less than 70 pc FWHM (Thean et al. 2000). In contrast, the optical images of the S2s show a distorted nuclear region caused by dust extinction and the presence of bars. The SBcb NGC 7582 is crossed by a dust lane along its major axis (Regan & Mulchaey 1999). $H\alpha$ imaging reveals a continuous distribution of HII regions along its central disk or bar (Hameed & Devereux 1999). The optical and NIR emission of the SBbc NGC 7496 is dominated by a long bar along its major axis, and its central $20''$ emission shows a peanut-shaped bulge (Mulchaey, Regan & Kundu 1997). The *LM*-band images of these two S2s (Fig. 1) show, however, rather ordered elliptical isophotes, particularly in NGC 7582. In NGC 7496, the peanut-shaped morphology disappears, the *L*-band image revealing instead symmetric extended emission at opposite sides of the nucleus, presumably from the central bar. At 8.4-GHz (Thean et al.), NGC 7582 is resolved in a peak and diffuse emission extending over ~ 1 kpc size whereas NGC 7496 is unresolved down to a region of 43 pc FWHM.

In the *LM*-bands the innermost 90 pc emission of all three galaxies is however dominated by a central point source. To disentangle the nuclear component from the host galaxy, the azimuthally averaged radial luminosity profiles from *J*- to *M*-band were deconvolved into an unresolved point source component (AGN) and a bulge component (host galaxy). In the *LM*-band images, the point source component was approximated by the Moffat fit derived from the star observed close in time, while the bulge component was approximated by a de Vaucouleurs law.

For NGC 7582, the extended emission was also alternatively fit with an exponential disk. In the *JHK*-band images, the unresolved component was directly approximated from the profiles of field stars in the galaxy frames. As the extension of the galaxies in these bands is larger than in the *LM*-bands, an additional disk component was included to better model the extended emission.

The resulting fits for NGC 7213 are shown as an example in Fig. 2., while the magnitudes and the fractional contributions of the unresolved and the extended component, and the modeled and observed luminosities in the *JHKLM* bands within different apertures for all Seyferts are given in Table 1. The contribution from the unresolved component increases with decreasing aperture and increasing wavelength. In the *J*-band, the emission is dominated by the host galaxy in the S1 NGC 7213 and in the S2 NGC 7496, and accounts for $\sim 50\%$ in the S2 NGC 7582. In the *K*-band, the host galaxy contribution is already reduced to $\sim 50\%$ level, while in the *LM*-bands, the emission is dominated by the unresolved component in all three Seyferts.

The spectral energy distributions (SED) of the nuclear and stellar components from *J*- to *M*-band within a $1''$ radius aperture (~ 150 pc) are shown in Fig. 3., along with similar data on NGC 1068 in a $0.6''$ aperture (Marco & Alloin 2000). The *K*- to *M*-band SED of the unresolved nuclear component is in all galaxies well fit by a grey blackbody with temperature $T = 500 - 800$ K. This hot dust resides in a region $< 70-90$ pc from the nucleus. Note, however, that the *JH*-band SED of the unresolved component clearly departs from that followed at longer wavelengths. The *J-H* and *H-K* colors (cf. magnitudes in Table 1) indicate much hotter dust. For all galaxies, the best fit to the *JH*-band emission indicates a dust temperature in the range $T = 800 - 1600$ K, close to the graphite sublimation temperature. However, the temperature of this dust component may be much cooler if an additional contribution by bremsstrahlung from the cooling of nuclear photoionized gas at $T = 10^4$ K is considered (see e.g. Contini & Viegas 2001).

Overall, the *J-H*, *H-K* and *K-L* colors of the unresolved component are much redder than those found in quasars (Hyland & Allen 1982). This difference is probably due to the still dominant contribution from the host galaxy, particularly in the *JH*-bands, in the central 150 pc region (Table 1), which renders the estimate of the unresolved component subject to large uncertainties. The *K-L* colors are also redder than those derived for the central region of NGC 1068 ($K-L = 1.8 \pm 0.2$; Marco & Alloin 2000), although note that the contribution from the host galaxy in the *K*-band was not removed in this galaxy. This situation is reversed when comparing the *L-M* colors: whereas in our three Seyferts $L-M \sim 0.7$, in NGC 1068 $L-M = 1.6 \pm 0.4$, indicating that the emission peak of the unresolved component is toward even longer wavelengths in NGC 1068.

On the other hand, the SED of the host galaxy shows an opposite trend from that of the unresolved component, namely a smoothly decreasing contribution from *J*- to *M*-band. The stellar contribution appears to be unimportant in the central 80 - 100 pc region in the *LM*-bands, whereas it dominates in the *JHK*-bands, and also at larger distances in all bands. The *J-H* and *H-K* colors (Table

1) are close to those of giants and supergiants (Koorneef 1983) and of normal spirals (Willner et al. 1984). The $K-L$ colors are much redder than in normal spirals but this is expected as the unresolved component dominates the nuclear L -band light.

Finally, at slightly larger scales (radius > 100 pc), the L -band emission from the host galaxy of NGC 7582 deserves particular attention. The subtraction of a bulge model from the L -band image reveals residual clumps of emission between 150 and 300 pc radius along the major axis of the galaxy (Fig. 4). These clumps are located along the disk/bar of HII regions seen also in $H\alpha$ (Hameed & Devreux 1999). These clumps probably represent individual dust cocoons heated by the underlying ring of powerful star forming regions to temperatures high enough to emit in the L -band and beyond. The $L-M$ colors of the clumps indicate relatively hot dust, $T > 800$ K, but these estimates are rather uncertain as the colors are averaged over the entire galaxy between 150 and 300 pc radius.

4. CONCLUSIONS

Deep, high spatial resolution L - and M -band imaging of three nearby Seyferts (two S2s and one S1) has allowed for the first time at these wavelengths to separate the AGN from the host galaxy emission. Regardless of the Seyfert type, in all three galaxies the unresolved nuclear component dominates the LM -band emission within < 90 pc diameter central region. The contribution of this component in the JHK -bands is, on the other hand, $< 50\%$. Together with literature AO data for NGC 1068, the K - to M -band SEDs of the unresolved component are well accounted for by dust emission with temperature $T = 500 - 800$ K in all cases.

The expected signature for central obscuring material – the putative disk or torus – is not seen in these galaxies. If typical sizes of the obscuring region are in the 80 pc range (cf. NGC 1068) the resolution of our data is just at the limit to resolve it. Future AO observations will provide a definitive answer. Interesting, recent $10\ \mu\text{m}$ imaging of the S2 NGC 7582 reveals a nuclear disk structure just at the right position, about perpendicular to the radio axis of the galaxy (Acosta-Pulido et al. 2002). We note that contrarily to the relative high polarization, $P \sim 16\%$, measured in NGC 1068, and interpreted as due to scatter nuclear light from its hidden S1 nucleus (Antonucci, 1993), the reported values for these galaxies are very low, $\sim < 1\%$ (Brindle et al. 1990), and probably not intrinsic to the sources.

The contribution of the host galaxy in the LM -bands is negligible within the central 90 pc region, but increases

with radius and accounts for $> 50\%$ of the integrated LM -band emission. The total extent of the host galaxy emission in the L -band is ~ 1 kpc in all three Seyferts, whereas the M -band emission is more compact, with average size ~ 500 pc.

The overall morphology of the galaxies at these wavelengths is rather relaxed. Particularly, the emission in the L -band contrasts with the distorted optical and NIR emission of the two S2s. The lack of a prominent nucleus in the optical images contrasts with the bright nucleus seen in the LM -band images of the S2s. In particular, the nucleus of NGC 7582 is as bright as that of the S1 NGC 7213 in the LM -bands. Note that NGC 7582 is heavily absorbed, with $N(\text{H}) = 1.67 \times 10^{23}\ \text{cm}^{-2}$ (Turner & Pounds 1989). Correcting for this absorption, its hard X-ray (2-10 keV) luminosity is $4 \times 10^{42}\ \text{erg s}^{-1}$, of the same order as that in NGC 7213 (Nandra & Pounds 1994). Thus, the brightness of its nucleus in the LM -bands indicates that NGC 7582 harbors a nucleus as powerful as that in NGC 7213. In the radio domain, the core flux of NGC 7213 at 8.4-GHz is ~ 3.5 larger than that measured in NGC 7582 in this case over a region of 10 arcsec (cf. section 2); within the framework of the Seyfert Unifying Schemes the difference could be interpreted as due to emission from the jet pointing close to the line of sight in the case of NGC 7213.

The S2 NGC 7496, although at the same distance as the other Seyferts, appears to be intrinsically weaker. It is also heavily absorbed, with $N(\text{H}) \sim 5 \times 10^{22}\ \text{cm}^{-2}$ (Krupe, Canizares & Urry 1990), but the derived absorption-corrected hard X-ray (2-10 keV) luminosity is only $\sim 1 \times 10^{42}\ \text{erg s}^{-1}$, much lower than in the other cases. Its 8.4-GHz core emission is also ~ 14 times lower than in NGC 7582. The LM -band luminosities of the unresolved component are also ~ 3 magnitudes fainter than in the other two Seyferts, altogether confirming NGC 7496 as the weakest of the three AGN.

Finally, for NGC 7582 we report to our knowledge the first detection of a star forming ring around a Seyfert nucleus in the L -band. This detection highlights the potential of high spatial resolution studies in the $3 - 5\ \mu\text{m}$ range to reveal important circunuclear emission in AGN.

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FIG. 1.— Contour plots of the L - and M -band images of the three Seyferts. North is up and east to the left. The $2''$ scale bar, and contour plots of the standard stars observed for PSF determination are shown in the bottom left and bottom right corner of each panel, respectively.

FIG. 2.— Luminosity profile fits in the J - to M -bands of NGC 7213. Each panel shows the azimuthally averaged observed luminosity profile (filled circles), the contributions from the point source (short-dashed line) and bulge (long-dashed line) components, and the fit to the observed profile from the convolution of these components (solid line).

FIG. 3.— The SED of the Seyferts from J - to M -band within a $1''$ radius aperture (~ 150 pc average size). The unresolved nuclear component and the host galaxy component are plotted as circles and stars, respectively. In the bottom panel are shown for comparison the results for NGC 1068 within a $0''.6$ diameter radius aperture (~ 33 pc) from Marco & Alloin (2000). For NGC 1068, all emission is assumed to be nuclear, as no deconvolution was applied in this case.

FIG. 4.— The L -band image of NGC 7582 after removal of the host galaxy with a bulge model. Outside the central region, which is masked for the sake of clarity, the residual emission shows a ring of circunuclear clumps interpreted as powerful star forming regions.

TABLE 1
FITTING RESULTS AT DIFFERENT WAVELENGTHS IN THREE APERTURES.

λ	Comp	NGC 7213				NGC 7496				NGC 7582			
		$1''0$	$2''0$	$4''0$	$1''0$	$2''0$	$4''0$	$1''0$	$2''0$	$4''0$	$1''0$	$2''0$	$4''0$
J	nucl	.../...	14.88/ 8	14.62/ 4	.../...	15.48/21	15.30/12	.../...	12.56/61	12.98/39	...	...	...
	host	.../...	12.30/92	11.23/96	.../...	14.09/79	13.18/88	.../...	13.59/39	12.51/61	...	...	...
	total	.../...	12.21 12.19	11.19 11.17	.../...	13.82 13.81	13.04 13.04	.../...	12.56 12.05	11.97 11.29	...	...	...
H	nucl	.../...	13.29/17	13.11/ 9	.../...	14.46/26	14.27/16	.../...	11.34/80	11.24/62	...	...	...
	host	.../...	11.50/83	10.47/91	.../...	13.37/74	12.47/84	.../...	12.84/20	11.76/38	...	...	...
	total	.../...	11.31 11.29	10.38 10.35	.../...	13.03 13.01	12.28 12.28	.../...	11.10 10.74	10.72 10.12	...	...	...
K	nucl	.../...	11.62/39	11.49/22	.../...	13.27/44	13.14/38	.../...	9.98/90	9.87/79	...	...	...
	host	.../...	11.16/61	10.16/78	.../...	12.96/56	12.14/72	.../...	12.32/10	11.26/21	...	...	...
	total	.../...	10.61 10.60	9.88 9.86	.../...	12.38 12.37	11.78 11.78	.../...	9.87 9.66	9.61 9.19	...	...	...
L	nucl	8.44/91	8.13/83	8.05/69	11.47/89	11.27/79	11.26/61	8.30/89	8.08/77	8.07/63	...	...	...
	host	10.95/ 9	9.82/17	8.91/31	11.77/11	12.67/21	11.74/39	10.52/11	9.42/23	8.63/37	...	...	...
	total	8.34 8.36	7.92 7.95	7.64 7.67	11.34 11.38	11.00 10.94	10.72/10.62	8.17 8.17	7.81 7.82	7.63 7.57	...	...	...
M	nucl	7.71/93	7.50/87	7.45/75	.../...	.../...	.../...	7.63/95	7.42/89	7.37/77	...	...	...
	host	10.60/ 7	9.54/13	8.65/25	.../...	.../...	.../...	10.86/ 5	9.65/11	8.68/23	...	...	...
	total	8.34 8.36	7.92 7.95	7.64 7.67	... 11.09	... 10.59	... 10.53	7.58 7.59	7.29 7.30	7.09 7.10	...	...	...